FUEL CYCLE OF BREST REACTORS. SOLUTION OF THE RADWASTE AND NONPROLIFERATION PROBLEMS

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Abstract. Fast reactors with a nitride fuel and a lead coolant (BREST) have low excessive in-core plutonium breeding (CBR ~1.05) and do not have breeding blankets. The fuel cycle of BREST reactors includes stages that are traditionally considered in a closed fuel cycle of fast reactors excluding the breeding blanket cycle, namely in-pile fuel irradiation, post-irradiation cooling of spent FAs (SFAs); SFA transportation to the recovery shop, SFA dismantling, fuel extraction and separation of the SFA steel components, radiochemical treatment, adjustment of the fuel mixture composition, manufacturing of nitride pellets, manufacturing of fuel elements and fuel assemblies, interim storage and transportation to the reactor. There is a radioactive waste storage facility at the NPP site. The fuel cycle of fast reactors with CBR of ~1 does not requires plutonium separation to produce "fresh" fuel, so it should use a radiochemical technology that would not separate plutonium from the fuel in the recovery process. Besides, rough recovered fuel cleaning of fission products is permitted (the FP residue in the "fresh" fuel is 10^{-2}-10^{-3} of their content in the irradiated fuel) and the presence of minor actinides therein causes high activity of the fuel (radiation barrier for fuel thefts). The fuel cycle under consideration "burns" uranium-238 added to the fuel during reprocessing. And plutonium is a fuel component and circulates in a closed cycle as part of the high-level material. The radiation balance between natural uranium consumed by the nuclear power closed system and long-lived high-level radioactive waste generated in the BREST-type nuclear reactor system is provided by actinides transmutation in the fuel (U, Pu, Am, Np) and long-lived products (Tc, I) in the BREST reactor blanket and by monitored pre-disposal cooling of high-level waste for approximately 200 years. The design of the building and the entire set of the fuel cycle equipment has been completed for a BREST-OD-300 experimental demonstration reactor, which will implement the basic features of the BREST reactor fuel cycle.

Large-scale nuclear power – the industry that can meet about half of the future demand for electricity production – must comply with a set of criteria for safety, economics and fuel cycle strategy. This paper discusses the BREST fast reactor fuel cycle concept from the viewpoint of its specifics and ability to meet the requirements for nonproliferation of nuclear materials and to establish a balance between the generated radioactive waste and the mined natural uranium.

Design premises for the fuel cycle of BREST reactors:

- Periodic fuel reprocessing and fabrication in a closed cycle.
- Full Pu reproduction in the core without U blankets and with BR~1.05.
- Transmutation of most hazardous long-lived actinides (as part of fuel) and fission products (irradiation outside of the core). Profound cleaning of radioactive waste to remove these nuclides. Radiation balance between buried RW and uranium mined from earth.
- Rough fuel cleaning from fission products during reprocessing. Fuel facilities in the closed cycle should be unsuitable for Pu recovery from spent fuel (technological support to nonproliferation).

- On-site fuel facilities to avoid shipment of large amounts of high-level and fissile materials.
- Cost-effectiveness of the entire complex (reactor and fuel cycle).

The BREST-OD-300 NPP design includes the plant proper with a demonstration liquid-metal reactor BREST 300 MWe in capacity, the on-site closed fuel cycle and the complex for radwaste treatment and storage. The design studies have confirmed the feasibility of building BREST reactors of various capacity (e.g. 600 and 1200 MWe) for the large-scale power industry of the future, following the same principles as those designed into the 300 MW reactor. The BREST-OD-300 facility is a pilot, demonstration power unit meant to validate and further develop the design features adopted both for the reactor facility and for the on-site fuel cycle with a radwaste management system. On completion of the essential studies, the power unit is to go into commercial operation in the grid. Subsequent commercialisation is expected to proceed with the NPP comprised of two BREST-1200 units and having an on-site fuel cycle, which has gone as far in its development as a full-fledged conceptual design (Fig. 1).

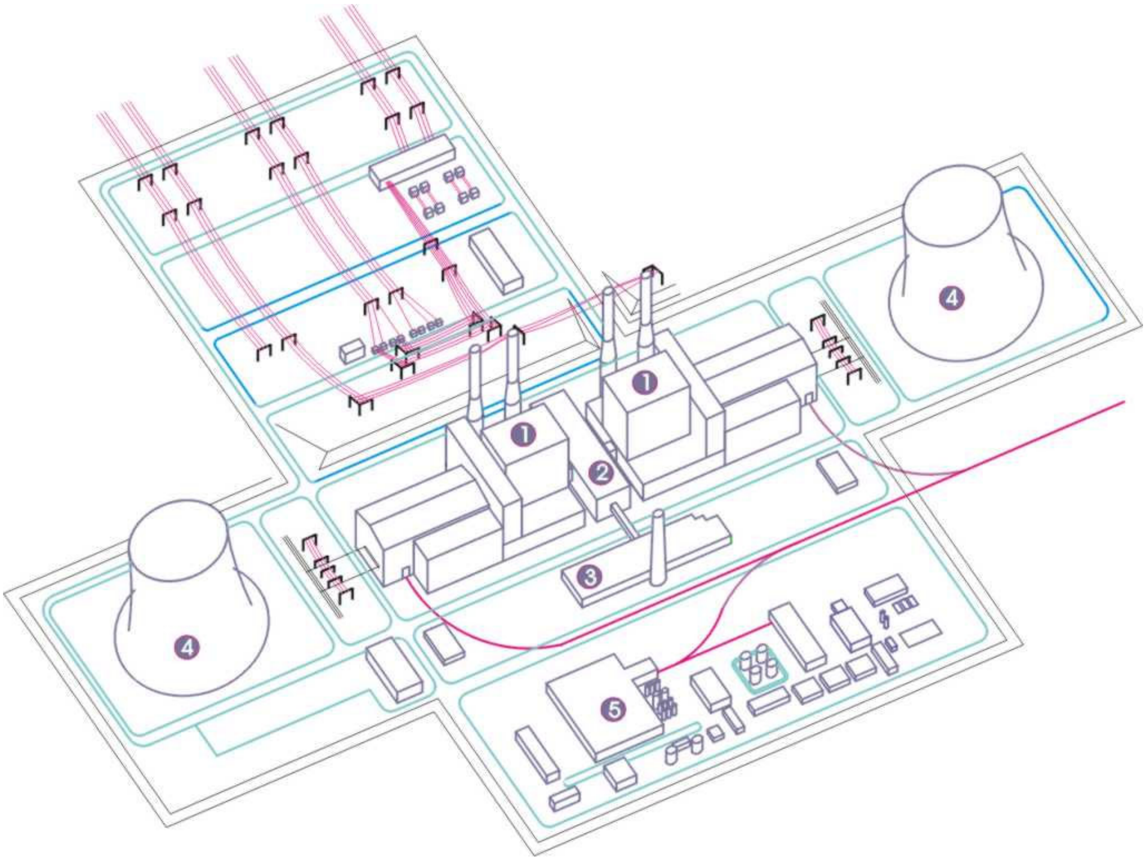


Fig. 1. General layout of the BREST-1200 NPP:
1 - BREST-1200 reactor building; 2 - building of the on-site closed fuel cycle; 3 - radwaste treatment and storage building; 4 - cooling tower; 5 - auxiliary buildings.

According to current expectations, the BREST-1200 plant design will rely on the BREST-OD-300 developments tried out in operation: fuel rods and assemblies, basic equipment of the plant proper and its on-site cycle. Transfer to the higher installed capacity will be achieved largely by increasing the number of the tried-out components. Thus, the transition from the pilot plant to a commercial facility may be effected with minimised time and money spent on it. It should be also mentioned that the on-site fuel cycle will be shared by the two power units.

The BREST fuel cycle promises virtually unlimited expansion of the fuel resources available to the nuclear power industry due to recycling of U-Pu-MA fuel of equilibrium composition (CBR ≈ 1,05) which will require addition of but small quantities of depleted or natural uranium to compensate separated fission products [1]. The fuel cycle arrangement allows attaining the radiation equivalence of nuclear materials with allowance made for their migration. To this end, the radioactivity and the nuclide composition of the waste subject to burial should be such that the heat and the stability of the buried materials and the degree of migration risk of the nuclides, with regard to their respective biological hazards, should be at least no worse than those found at natural uranium deposits [2].

An on-site nuclear fuel cycle (SNFC) has been developed for the BREST-OD-300 reactor. Designed SNFC must provide reprocessing and fabrication of fuel of BREST-OD-300 and BN-800 reactors with nitride core (Table 1).

Table 1. Main characteristics of the on-site nuclear fuel cycle

Characteristic	Value
Annual plan for FA reprocessing and fabrication, FA/year:	
BREST-OD-300	29
BN-800	259
Pu going to waste, %	0.5
Annual consumption of some materials and agents:	
Depleted uranium, kg/year	998
Hydrogen gas, nm^3/year	3808
Liquid nitrogen, kg/year	5000
Liquid argon, t/year	900
Helium gas, nm^3/year	100
Steel for BREST, kg/year	3000
Steel for BN, kg/year	12000
Zinc, kg/year	2430
Chlorine, potassium, lithium chlorides, kg/year	630
Staff	240
Operating power of process equipment, total kW	2240
Total area of the building, m^2	31500
Space (volume – либо то, либо другое) of the building, m^3	236400
Stack releases after filtering (including RW treatment facilities)	
Individual isotopes, Bq/year:	
^{3}H	$4.09 \cdot 10^{9}$
^{85}Kr	$7.67 \cdot 10^{15}$
^{129}I	$1.22 \cdot 10^{7}$
Aerosols, total (including short-lived), Bq/year:	
α-active	$1.77 \cdot 10^{7}$
β-active	$1.49 \cdot 10^{10}$

Design documentation consists of:

- master plan, fuel cycle buildings, RW storage facilities and transportation links;
- design of equipment to be used at all stages of the fuel cycle;
- automation, communication lines and alarms;
- environmental protection;
- cost estimates.

The BREST-OD-300 fuel cycle consists of the stages usually included in the closed fuel cycle of fast reactors, except for the fuel cycle of breeding blankets:

- in-pile fuel irradiation (4-5 years);
- post-irradiation cooling (1 year) of spent fuel assemblies (SFA);

- SFA transportation to the SNFC building;
- SFA cutting to extract fuel and separate steel components;
- radiochemical treatment of fuel (reprocessing);
- adjustment of fuel composition;
- fabrication of nitride pellets;
- fabrication of fuel rods and fuel assemblies;
- temporary storage of fuel assemblies;
- FA transportation to reactor.

The cycle includes collection of radioactive waste, their partition and preparation for storage. The entire process of fuel recycling takes place in the reactor building and in the adjacent building of the on-site nuclear fuel cycle. There is storage facility at the site to accommodate radioactive waste.

SNFC of BREST-OD-300 is designed for a capacity of 17.6 t (U,Pu)N/year under conditions of the first core fabrication and for ~ 3.5 t (U,Pu)N/year under conditions when the fuel is regenerated and refabricated. Main characteristics of the on-site nuclear fuel cycle are presented in Table 1. Key requirements for reprocessing technique for BREST fuel is presented in Table 2. The fuel cycle building layout is shown in Fig. 2.

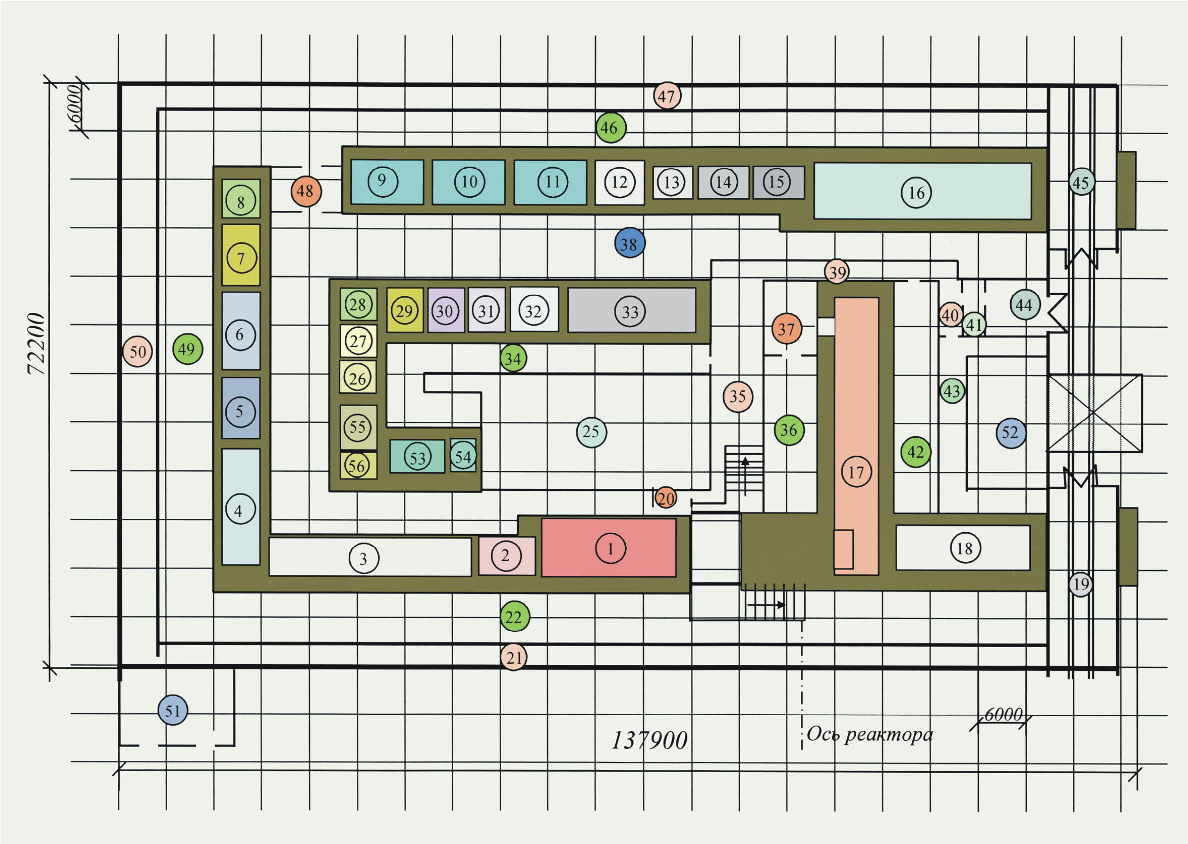
Table 2. Key requirements for reprocessing technique for BREST fuel

Source material	Nitride U-Pu-MA fuel, ~9% FP
Uranium and plutonium are kept together	
RW cleaning from actinides	<0.1 % remaining in fuel
Fuel cleaning from FP	0.1-1 % remaining in fuel
End product	metal or nitride (U+Pu+Am+Np)
Sr, Cs separation from RW	1-5 % remaining in fuel
I, Tc separation from RW	1-5 % remaining in fuel
Actinide content in separated Sr, Cs, I, Tc fractions, no more than	0.1 % (at)
Cm separated from fuel	to be stored out of pile during 50 to 70 years, with Pu (Cm decay product) returned in reactor
Content of Cm in “fresh” fuel	1-10% remaining in fuel

The BREST-OD-300 fuel cycle design involves electrochemical reprocessing of irradiated nitride fuel with separation of uranium+plutonium and MA in molten LiCl-KCl. The basic features of such a technology were developed at the Argonne National Laboratory (USA) and were elaborated in a whole number of efforts, including those undertaken by NRIIM. The fuel cycle equipment was designed by a special organisation of SverdNIIkhimmash.

SNFC technology involves the following main processes:

– separation of cladding and lead bond from fuel by dissolving the active part of fuel assembly in molten metallic zinc;
– preparation of LiCl-KCl salts with minimum oxygen content and melt saturation with uranium and plutonium trichlorides;
– anodic dissolution of irradiated nitride fuel in molten salts;
– sedimentation at the solid cathode of metallic U, Pu, Np, Am and some Cm;
– periodic additional separation of U and Pu from molten salts under altered conditions of electrochemical process during electrolyte recovery;
– vacuum melting of mixed metallic U-Pu-Np-Am-Cm + 10 % RE at 1000 ^{o}C;
– granulation, hydrogenation and nitration of the metallic mixture, production of nitride powder, and distillation of electrolyte to be returned to the electrolyser.



No. in plan	Work area	No. in plan	Work area
1	Area for cutting of fuel assemblies and opening of fuel rods	21, 35, 39, 40, 47, 50	Corridor
2	Chamber for fuel preparation for regeneration	22, 34, 36, 42, 46, 49	Control room
3	BREST fuel regeneration chamber	23, 24, 38	Maintenance corridor
4	Nitride preparation chamber	25	Ventilation chamber
5	Storage of powder containers	26	Crushing chamber
6	Chamber for moulding powder preparation	27	Carbothermy chamber
7, 29	Moulding chamber	30	Blending chamber
8, 28	Reloading lock	31	Plutonium oxide storage chamber
9, 10, 11	Drying and sintering chambers	32	Laboratory
12	Storage of sintered pellets	33	Test laboratory
13	Complex for inspection of pellets and components	41	Uranium unloading compartment
14	Complex for assembly and sealing of fuel rods	43	Area for preparation of claddings and fuel rod components
15	Complex for outgoing inspection of fuel rods	44	Anteroom for components
16	Storage of fuel rods	45	Anteroom for fuel rods
17	Fuel assembly fabrication area	51, 52	Personnel access point
18	Fuel assembly handling chamber	53	Facility for decontamination of large components
19	Anteroom for BN-800 fuel assemblies	54, 56	Depot
20, 37, 48	Additional sanitary area	55	Facility for decontamination of small components

Fig. 2. Layout of the BREST-OD-300 fuel cycle facilities (plan at elevation 0.0)

All the processes are provided with systems for cleaning the released gases from aerosols and volatile radioactive elements (tritium, iodine, krypton).

A distinguishing feature of the fuel cycle arrangement is the unattended mode of its processes, i.e. complete remote control of the basic process, equipment adjustment, repair and maintenance.

1. Technological Support to Nonproliferation of Weapons-Grade Materials in the Closed Fuel Cycle of BREST Fast Reactors.

Fast reactors do not need enriched uranium, i.e. enrichment services may be curtailed and then given up with time. Pu and spent fuel will be gradually removed from existing storage facilities and spent fuel cooling pools at NPPs to be used for fabrication of the first cores for fast reactors (spent fuel reprocessed to recover Pu). Initial recovery of Pu and fabrication of the first cores for fast reactors should be carried out at safeguarded facilities in nuclear countries (Fig. 3).

The BREST-OD-300 design is notable for its focus on engineering rather than organisational provisions for proliferation resistance. In the fuel cycle of BREST reactors with CBR~1.05:

- all FAs of the core contain the same amount of Pu;
- there are no uranium blankets breeding weapons-grade Pu because they are not needed;
- both before and after regeneration, the BREST reactor fuel is unfit for production of nuclear weapon;
- there is no need to recover Pu for fabrication of fresh fuel (it is suffice to separate fission products and add depleted U). Hence, reprocessing may be used because it is not suitable for Pu recovery;
- there is no need for U enrichment;
- surplus Pu is used as part of U-Pu mixture for fabrication of the first core of new reactors;
- reprocessed fuel is partially cleaned from fission products (fresh fuel contains 10^{-2} – 10^{-3} FPs present in spent fuel) and incorporates minor actinides (MA), which makes fuel highly radioactive (radiation barrier to fuel thefts).

In the fuel cycle under discussion, reactors burn ^{238}U added in fuel during reprocessing. Pu is part of fuel and recycles in the closed cycle as part of highly active mixture (combustion catalyst for ^{238}U).

The fuel cycle of BREST-OD-300 reactors is arranged without transporting irradiated fuel to an external reprocessing facility. After one-year cooling in the in-pile storage, the irradiated fuel assemblies are passed on to the fuel cycle facility via a transport passageway connecting it with the reactor compartment. Thus, the design eliminates all the risks and costs related to fuel shipment for regeneration and obviates the need for the associated handling and transportation equipment.

The electrochemical reprocessing will be modified or changed in BREST-1200 SNFC design to provide the protection from plutonium extraction.

2. BREST-OD-300 radwaste management

Attaining radiation equivalence

Pu and Am are principal contributors to potential long-term biological hazard of spent fuel (cooling time 10^2 – 10^5 years). Radiation balance between natural uranium used in the closed nuclear power system and long-lived radioactive waste produced in the system of large scale nuclear power based on reactors of the BREST type can be attained through (Fig. 3):

- profound cleaning of radioactive waste from actinides;
- actinide transmutation as part of fuel (U, Pu, Am, Np, Cm) and long-lived products (Tc, I) in the out-of-core zones of BREST reactors;
- monitored storage of high-level waste during ~200 years prior to disposal to reduce their activity 1000 fold.

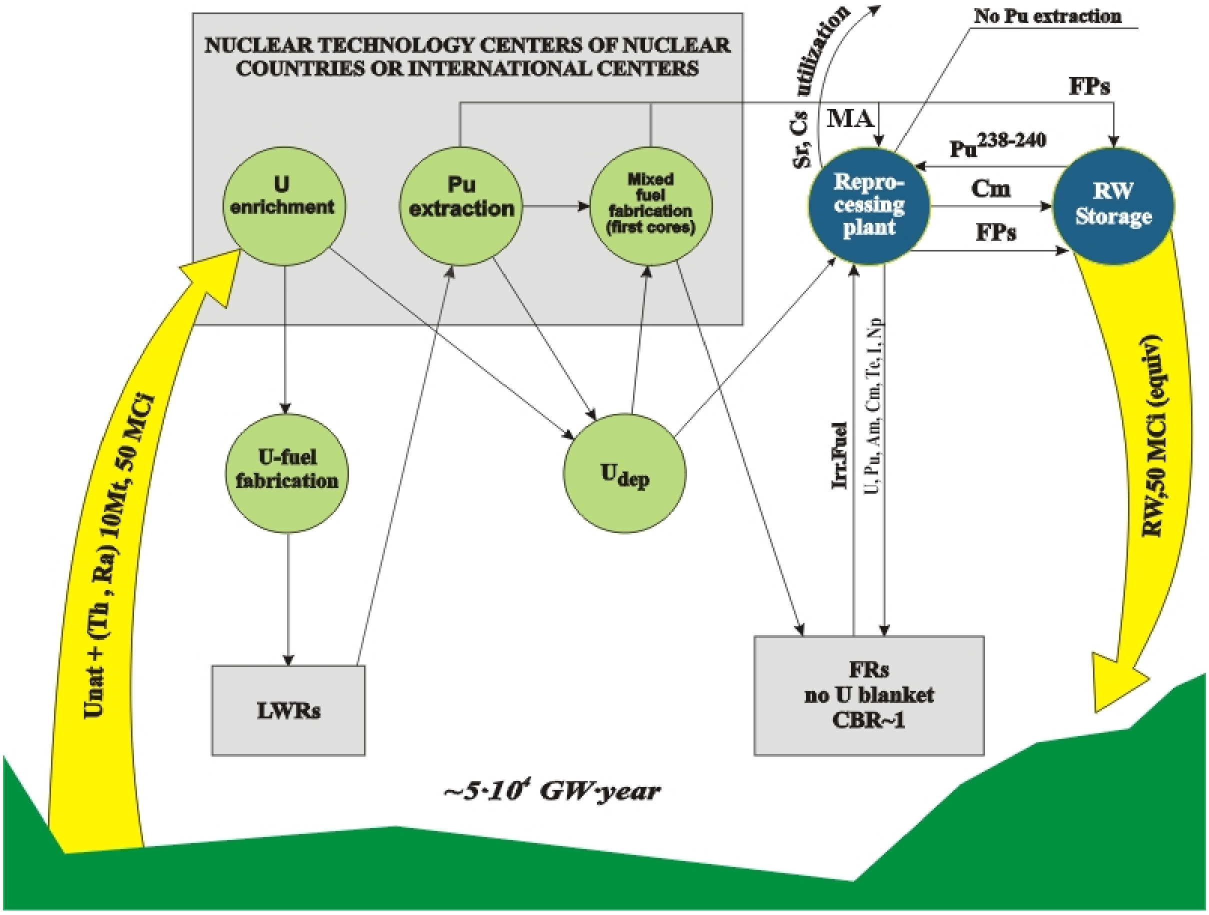


Fig.3 Tentative scheme of radiation-balanced proliferation-resistant closed nuclear fuel cycle of large-scale nuclear power

Management of liquid and solid radioactive wastes of the BREST-OD-300 plant is arranged in compliance with the requirements of radiation-equivalent disposal.

The generated waste may be conventionally divided into two major categories:

- low- and medium-level liquid and solid wastes which are largely typical of NPPs. They emerge in a broad spectrum and relatively large volumes;
- high-level solid waste produced in the fuel cycle during regeneration of irradiated fuel and preparation of mixed uranium-plutonium fuel. This waste is distinguished by small quantities, very high specific activity, intensive heat release and high content of long-lived nuclides.

Waste management for the first category follows largely the traditional procedure (filtering, biofiltering, evaporation, sorption, concentrate solidification for liquid radwaste; sorting, pressing, burning for treated solid radwaste; compacting or long-term storage for untreated solid radwaste).

For the second category, waste management has no precedent either at Russian NPPs or at any foreign facilities.

Opening of fuel rods and regeneration of irradiated nitride fuel give rise to high-level waste of the following categories:

- noble elements (ruthenium, rhodium, palladium, etc.) as well as molybdenum, zirconium, technetium present as particles in molten salts (electrolyte). Their total quantity makes 0.32 t per year. Separation is carried out with the use of a porous metal filter which is reconditioned by molten lead. When these fission products build up to 10 % by mass, they are removed into a container which after cooling, sealing and decontamination is sent on for long-term storage. Technetium is fractionated, with previous oxidation and distillation of the generated oxide Tc_2O_7. Technetium oxide undergoes condensation and will be stored before going to the reactor for transmutation;

- chlorides of rare-earth, alkali-earth and some other elements, mixed with electrolyte in the proportion of 1:1. Their total quantity is estimated at 1.8 t per year. Electrolyte regeneration involves previous extraction of uranium and plutonium, followed by separation of fission products through zonal crystallisation. The cleaned electrolyte is reused. The fraction of rare-earth elements and curium is enclosed in a nickel matrix with a fill of 10 % by mass. The alkali-earth metals fraction is enclosed in a copper matrix with a fill of 10 % by mass. Cesium chloride is placed in a calcium phosphate matrix with the same fill;
- fuel claddings and other structural components of fuel assemblies. Their total quantity is assessed at 3 t per year. The ingots together with spent crucibles are loaded into containers which, upon sealing and decontamination, are sent away for long-term storage. Consideration is being given to the possibility of recycling this metal in the on-site fuel cycle, after its treatment by induction melting;
- spent gas filters and gas absorbers. With their service life over, these components are to be loaded into containers and filled with matrix material (cement).

The radwaste management design provides for waste division into separate flows with regard to its activity, aggregative state and other characteristics, with subsequent treatment of each flow in the most efficient and safe way. The treatment results in transportable final products of minimised volume, which safely confine their radionuclides during transfer, storage and disposal.

The engineering design of the radwaste handling system in the on-site fuel cycle calls for further research and development work to validate the design solutions, especially those pertaining to regeneration, fractionation and treatment of high-level waste resulting from fuel regeneration and fabrication.

3. Near-term activities on the BREST-OD-300 fuel cycle

1. Setting up a mock-up fuel cycle in NIIAR, Dimitrovgrad (2003-2004):
   - cutting of a spent fuel rod;
   - fuel reprocessing;
   - adjustment of fuel composition;
   - fabrication of nitride pellets;
   - fabrication of a new fuel rod.

2. Improvement of the system of RW fractioning and storage to reduce the volume of storage facility intended for long-term storage of radioactive waste (2003 – 2005).

3. Improvement of FC components based on trial operation (2003 – 2008).

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